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by

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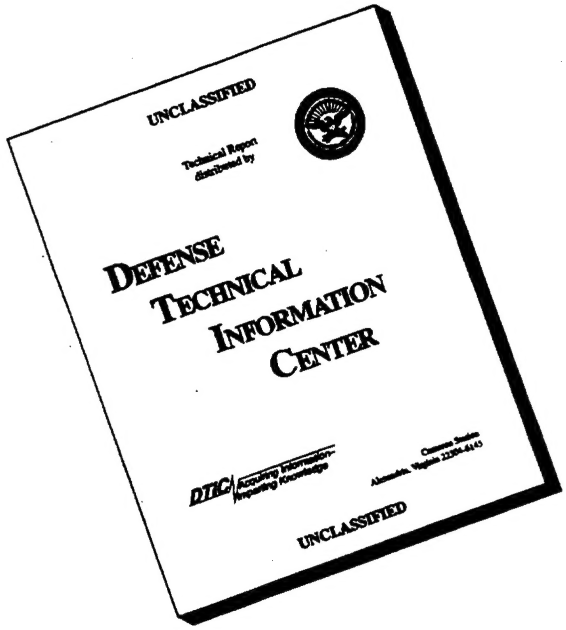

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Precise Orbit Determination with GPS

H. Rim, G. E. Powell, B.D. Tapley, et al.

Abstract: The Global Positioning System (GPS) is likely to become a powerful means in precise orbit determination (POD) of low-orbiting Earth satellites as long as it can fully cover the satellites. With its continuous tracking and coverage capabilities, this system can realize not only conventional dynamic precise orbit determination, but kinematic orbit determination as well. Technically, by smoothing the pseudo-range measurement values derived from at least four GPS satellites by using the carrier wave measurement values, the geocentric position at the phase center of the antenna and the clock correction values of the user satellites can be determined. Therefore, the foregoing technology does not require a dynamic model to impose a force on a user satellite. The kinematic method is extremely sensitive to the effects from measurement models, such as the GPS sidereal error (either as a given or to be solved), signal multipath, receiver noise, etc. On the other hand, however, the dynamic method also suffers from effects caused by parameter errors and/or imperfections of the force model. With this scenario, a hybred arrangement was proposed designed for weighting the kinematic and dynamic algorithms by compensating for the process noise. Our project was focused on the investigating these orbit determination methods through a simulation and covariance analysis with several dynamic and measurement error models. The orbital uncertainty generated by these models was found to be roughly equivalent to the sidereal error estimated in processing actual GPS data. In this case, the covariance analysis, when adjusted, was able to reflect these errors and to reveal the characteristics of various filtering techniques.

1. Introduction

The United States National Aeronautics and Space Administration (NASA) and the French National Space Center (CNES) already started implementing a satellite altitude finding mission as part of the "Ocean Topography Experiment" (TOPEX/Poseidon), aimed at measuring ocean currents and tides from space. To derive ocean current and tide measurement values of practical interest, an extremely accurate measurement of the ocean surface topography is required. The measurement precision is required to be ±13cm in the geocentric coordinate system and accordingly, the measurement precision for the radial component of TOPEX orbit should be within 13cm.

The selection of a proper TOPEX orbit can overcome a series of challenges related to this mission. That orbit must be able to cover the vast ocean with a high frequency incidence without being affected by tides. To achieve this, the first requirement is that the satellite track must repeat exactly at given time intervals. Such precise repetition (±1km) will reduce the effect of geodetic datum variation in space and will help in determining the variations of geostrophic ocean currents with data collected by the radar altimeter without needing to consider changing of the geodetic datum. It is not very difficult to meet the constraints of orbital track repeatability.

On the other hand, the sampling strategy of the altimeter proposed a set of strict criteria for the TOPEX orbit. This strategy depends on four inter-related characteristics (Stewart et al., 1986): 1) Ground grid density of the sub-satellite point orbital track on the ground; 2) Latitude range of the grid; 3) Angle between orbital tracks at the intersection point; and 4) Time interval of the repetition period. If any one of the criteria is given maximized, the other criteria have to be

correspondingly minimized. Therefore, an optimal overall design could not be realized unless a compromise was made. The TOPEX orbit design already managed to include all the foregoing characteristics into an optimal combination: TOPEX will be operating along an orbit with height 1333.8km and dip 63.1°, and the index distributive value of its radial orbit error is 13.3cm (Taply and Ries, 1987).

A preliminary estimate of the TOPEX orbit error suggests that the error due to the gravitational field is a major obstacle when employing the dynamic method to arrive at the orbit determination precision required in the TOPEX mission. To reduce the orbit error, the gravity model parameters can be adjusted by using ground observations. At present, however, the ground-based tracking system, unable to cover the global surface, may produce errors in determining gravity model parameters. These errors can be transformed into geography-related orbital errors and thus restrict the use of altimeter observation values collected by TOPEX.

A GPS demonstration receiver (GPSDR) will be mounted in TOPEX, designed to demonstrate the GPS potential in tracking low-orbiting Earth satellites. In this case, the major error source in the differential GPS dynamic tracking of TOPEX still is the uncertainty in the Earth's gravitational potential model. The GPEDR-collected GPS observation values will be the TOPEX orbit tracking data under nearly global and nearly continuous coverage within the range of ±65° latitude. Virtually, these continuous, global and high precision GPS observation values are extremely effective data in introducing gravitational modules (Mo) and raising TOPEX sidereal precision. Another way is to absorb gravitational and other dynamic error sources by estimating the noise acceleration from a coupling process of a group of TOPEX satellites.

With GPS-TOPEX data, the analytical staff of the Jet Propulsion Laboratory (JPL) carried out a research project on accurate orbit determination by using a so-called simplified dynamic method (Wu et. al, 1987). They processed the arc segment data for 2 hours with the covariance analysis method, and calculated an approximately 7cm TOPEX radial RMS error value below the process noise level of the optimal simplified dynamic method (Yunck et. al, 1990). The aim of this research project was to find out, through simulation and the covariance analysis system, the prospects of determining the precise orbit of the TOPEX platform with GPS-TOPEX data. To conduct this simulation, several error models must be constructed and the GPS sidereal errors that these models produce are roughly equivalent to those occurring in orbits estimated with actual GPS data.

2. Accurate Orbit Determination Technique Based on GPS

The accurate orbit determination methods based on GPS all rely differential tracking. As shown in Fig. 1, the position of all platforms is determined relative to a group of datum tracking stations, while the position of those non-datum ground receiver stations is to be adjusted (solved). However, there is a diversity of methods used for processing data from differential tracking systems, to be discussed in the following sections.

(1) Dynamic Orbit Determination

The dynamic orbit determination method is a classical algorithm, in which observable quantities derived at different instants will be incorporated into one particular epoch with the aim of estimating the state of that epoch instant. Such incorporating calculations are done by integration of equations, describing the movement of the satellites being measured (low-orbit satellites and GPS satellites). Dynamic orbit determination has two advantages. 1) During non-GPS tracking,

orbits of user satellites generally cannot be determined at every observation instant and therefore, all observation values have to be incorporated into a common epoch so as to determine the orbit at that particular instant. 2) If the measurement error turns out to be a random error with zero mean value, and if the force model can accurately describe the movement of the low earth satellite, then the least-squares solution method can be used to reduce the orbit error caused by measurement noise. As for the long-arc segment solution, most analysts prefer to use differential tracking and dynamic orbit determination to directly eliminate the clock error with a double-difference measurement value. The double-difference measurement value is a linear combination of four pseudo-ranges or phase integration ranges from two GPS satellites to two receivers. The double-difference measurement value formed by receivers i and j, and by GPS satellites l and m, can be written as

$$\Delta_{i,j}^{2,m} = \rho_i^l - \rho_i^m - \rho_j^l + \rho_j^m \tag{1}$$

Since double-difference data processing can directly eliminate the clock error and reduce the state-estimation vector dimension, the differential GPS tracking technique can generally eliminate the clock error of satellites and receivers. Nonetheless, to process the double-difference data (pseudo-range and/or phase integration), it is required to compensate for the correlation among measurement values. Here in this paper, another double-difference approach is presented; this approach serves to solve the clock deviation parameters at every measurement instant (the model is taken as the noise parameter of the white noise process). These two methods are equivalent (Wu, 1984; Wu, 1991), i.e. they contain the same information and roughly identical orbit errors, along with two hypothetical conditions: 1) that the white noise clock has an extremely high σ value and 2) that the correlation among double-difference measurement values is properly handled.

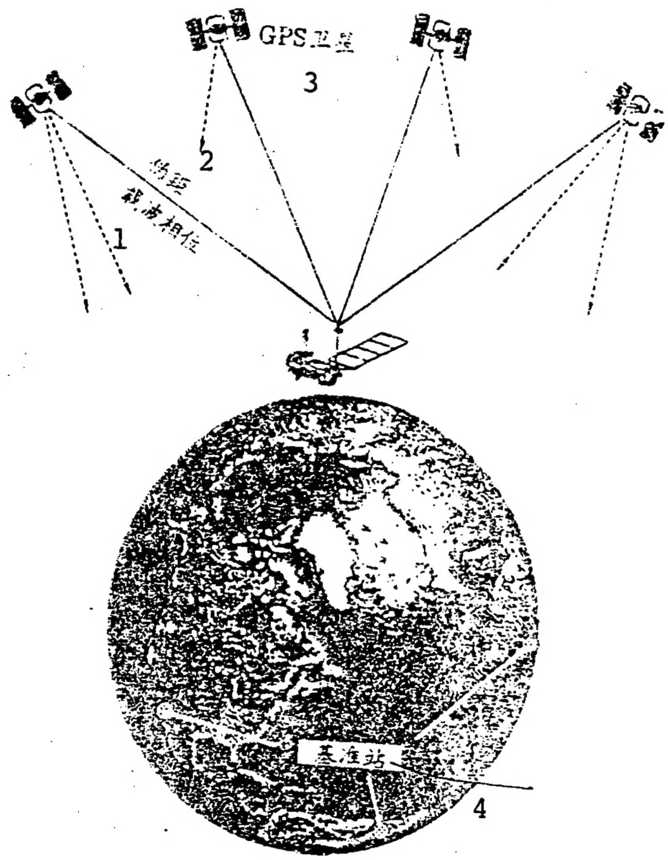

Fig. 1. Differential GPS Orbit Measurement
Key: (1) Carrier wave phase; (2) Pseudo range
(3) GPS satellite; (4) Datum station

As the error of the dynamic force model increases with time and often restricts the orbit determination precision of the long-arc segment low-orbit satellite, we are faced with two contradictory principles: 1) The longer the data arc segment, the more measurement values there are to be processed and therefore, the random measurement noise component of the orbit error can be reduced as much as possible through smoothing; 2) The longer the time between measurement instant and epoch to be solved, the larger the error introduced by the dynamic model error may be.

Errors of the dynamic model applied in this paper are listed in Table 1 and Table 2.

Table 1. Gravitational Error Model

Error Source	Specifications	Radial RMS(cm)
Earth GM	$0.001 km^3/sec^2$	0.7
Gravity	TEG-2 covariance	9.4
Sea tide	Optimal standard and CSR sea tide	2.5
Earth solid tide	3% error of K2	0.2
Total		10.2

Table 2. TOPEX Non-gravitational Error Model

Error Source	Specifications	Radial RMS(mm)
Atmospheric resistance	. Real: DTM of 3-hour random Kp . Nominal: Jacchia 71 of constant Kp . Cd, Cr adjustable	1.2
Solar radiation	. Real: 7x11x11; Nominal: 8x10x10 . Earth shadow radius has a 5km random error . Pitch angle 1° constant error . Cd, Cr adjustable	5.5
Earth radiation	. Reflection index has a 20% error . Both earth albedo and emission rate coefficient have a random error ($1\sigma=0.03$) . Cd, Cr adjustable	0.7
Thermal imbalance	12% error Cd, Cr adjustable	3.3
Total		5.5

(2) Kinematic Orbit Determination

For over 30 years, the dynamic orbit determination method has been the only approach in determining spacecraft orbits, in which a relationship is built between the satellite observation values derived at different instants and the satellite state at a particular epoch through integration of satellite movement equations. Yet as mentioned above, when the GPS constellation is full, a totally new method can be used to accurately determine the orbits of low earth satellites. This new kinematic method slightly modivies the concept of accurate orbit determination. This method imposes two requirements: 1) Collecting pseudo-range measurement values from at least four GPS satellites, and 2) Deriving carrier wave data together with long-term pseudo-range smoothing (without cyclic jump). Although the kinematic method requires the classical dynamic orbit determination technique to determine the GPS satellite orbit, it does not require a force model when user satellite orbit determination is involved. Unlike the dynamic method, the kinematic orbit solution takes the phase center of the GPS receiver antenna as a reference point instead of the satellite centroid. This method is capable of measuring the antenna phase center at a millimeter level of precision before emission (within the satellite-bound coordinate). However, this technique is limited by observation geometry, measurement error and GPS sidereal precision (either given or estimated). Table 3 lists the GPS measurement error sources adopted in our research project.

Table 3 Measurement Error Model

Error Source	Specifications	Radial RMS(mm)
Data noise	1cm	2.8
Troposphere	Real: Hopfield+1% error Nominal: Chao compression model(zenith delay adjustment)	0.6
Time mark	Allen variance $(\sigma_g=1.0^{-11},\ {}_1=1.0^{2},\ {}_2=1.0^{4})$	0.8
Antenna height	Rolling, pitch and off-course error 0.1^0	0.7
Earth orientation	. Random pole shi ft . Earth random turning . Random precession of the equinoxes, nutation error	0.4
Relative error of measurement station co-ordinate	. Random coordinate error 5cm . Random crustal plate velocity error . Random measurement station tide correction error	1.5
Total	All ambiguity is solved	4.7

(3) Simplified Dynamic Orbit Determination

The dynamic tracking method is extremely sensitive to the dynamic model error, while the kinematic method depends on relative geometry and measurement precision. Under different time and different orbit structures, dynamic error and measurement error vary greatly. Under this scenario, a hubrid orbit determination method was advanced, which, taking advantage of both kinematic and dynamic information, can weight the

relative significance of both dynamics and kinematics by compensating for the process noise in the user satellite force model. This method of hybrid character is referred to as simplified dynamic tracking (Wu et. al, 1987), which can estimate the state of the user satellite, respectively, with the pure dynamic method and and with the pure kinematic method at the ultimate values ($\sigma_1 \rightarrow 0$ and $\sigma_1 \rightarrow \infty$, where σ_1 is the stability uncertainty in the i-th processing of the interval force model process noise). Since low earth orbit spacecraft such as an earth observation system, space station, etc. may create extremely large force model errors, the simplified dynamic method is recommended, which can reach the best result in calculating the ultimate values with kinematic solutions (Yunck, 1990).

3. Simulation Software

(1) MSODP

The "Multiple Satellite Orbit determination Procedure" (MSODP) was developed by the University of Texas, where the Austin Space Research Center is located. With batch filtering technology, MSODP is used to estimate the epoch state of all satellites as well as related measurement deviation and force model parameters through non-square root Givens conversion. MSODP can process slant distance data and double-difference GPS phase observation values.

(2) OASIS

The orbit analysis and simulation software (OASIS) is used to carry out covariance analysis and research (Wu and Thornton, 1985). OASIS is a multiple satellite orbit analysis procedure developed by the Jet Propulsion Laboratory (JPL), designed to evaluate GPS satellite tracking with the simulation method and

the "Consider Covariance" analysis method. OASIS can solve linearized orbit determination problems, and can compensate for the process noise by using either a diagonal triangle (UD) or square root information filter (SRIF), coupled with the optimal Rauch-Tung-Streibei smoother (Bierman, 1977).

4. Simulation Steps

With repeated simulation, different GPS-based orbit determination schemes can be evaluated, and the actual error values from TOPEX GPS-based tracking can be determined. Literally, the simulation is accomplished in the following steps:

(1) Developing GPS tracking system dynamic and measurement models with MSODP. The GPS orbit precision derived from the system is equivalent to the orbit precision estimated by using actual GPS data, which is evaluated through a comparison between long-arc segment and short-arc segment solutions, and the overlap segment differentiation.

(2) Conducting, with these dynamic and measurement models, the dynamic Monte Carlo simulation of GPS-TOPEX orbit determination to respectively observe each dynamic and measurement error component.

(3) Carrying out a "Consider Covariance" analysis on GPS-TOPEX dynamic orbit determination with OASIS, and adjusting TOPEX and GPS satellite measurement and dynamic error models so that they are quantitatively identical to those in MSODP analysis.

(4) Selecting error models derived in (3) to carry out a "Consider Covariance" analysis of kinematic orbit determination and simplified dynamic orbit determination so as to evaluate the relative performance of the two methods.

5. Simulation Hypothesis

The classical form of satellite orbit determination is based on a given reference orbit of a particular satellite, which is taken for granted as a close approximation of an actual orbit. The precision of orbit determination will depends on the precision of tracking data, their geographic and time distribution, and the dynamic and measurement models which generate the reference orbit. This section introduces the nominal and actual models that these simulation systems adopt.

(1) Dynamic and Measurement Error Models

Research shows that the forces affecting the TOPEX orbit in the dynamic method include the Earth's gravitational force, solar and lunar gravitational forces, atmospheric drag, and solar radiation direct or reflecting pressure. Among other things, the major component is the uncertainty of the Earth's gravitational field. Table 1 lists detailed specifications of the gravitational error model used in the simulation, which indicate that the major forces affecting the GPS orbit involve Earth's gravitational force, solar and lunar gravitational forces, and especially the direct solar radiation pressure leading to the maximum error (Powell and Gaposchkin, 1987). Table 2 details the non-gravitational reference and actual models used in Monte Carlo simulation. As the major purpose of this simulation is to estimate the expected precision of TOPEX orbit determination under real conditions, we focused our effort on these major dynamic error sources and tried to introduce and employ actual data in estimating the possible dynamic orbit error at the same order of magnitude. Obviously, the dynamic simulation that we conducted, including carrier wave data noise, time mark error, earth orientation error, measurement station location error and troposphere model error all had a profound effect on the TOPEX orbit. Table 3 shows the detailed measurement model applied in

our project, where the error model listed generated, in comparing long-arc segment and short-arc segment solutions, a sidereal error, which was in agreement with the error occurring during orbit estimation with actual GPS data in both the order of magnitude and the curve shape. Table 4 indicates the system characteristics and error models adopted in Consider Covariance analysis; these models were selected so that the orbit error that they produced in dynamic orbit determination was roughly identical to the error introduced in Monte Carlo simulation. In other words, the Consider Covariance analysis was adjusted on the basis of Monte Carlo simulation, or the actual GPS data.

Table 4 TOPEX System Characteristics and Consider Covariance Analysis

Error	Model
System Characteristics	
TOPEX orbit:	1330km in height, dip=63.5^0
Number of GPS satellites:	24
Number of ground receivers:	6
Receiver field:	Full field
Receiver elevation cut-off angle:	TOPEX-5^0; ground receiver-10^0
Data types:	Double-frequency p-code pseudo range Double-frequency carrier wave phase
Measurement data interval:	5 minutes
Data arc segment:	24 hours
In-satellite receiver data noise:	50cm--pseudo range 0.5cm--carrier wave phase
Ground receiver data noise:	15cm--pseudo range 1.0cm--carrier wave phase
Estimated Constant Parameters with Uncertain Optics	
TOPEX state:	300m; 30cm/sec, each component
GPS satellite state:	3m; 3cm/sec, each component
Non-deep space network ground receiver:	20cm, each component
Receiver clock:	300 microseconds; white noise model

(Table 4 continued on the following page)

Table 4 continued

Estimated Statistic Parameters with Uncertain Stability

TOPEX clock:	30 milliseconds; white noise model
GPS clock:	300 microseconds; white noise model
Receiver clock:	300 microseconds; white noise model
Phase ambiguous parameters:	10km; invisible, white noise process noise
	1km; visible, constant parameters

Consider Deviation Parameters

Earth GM:	$0.001 km^3/sec^2$
Gravitational field error:	TEG-2 variance
GPS solar radiation pressure:	2.0%
GPS Y acceleration deviation:	$0.1 nm/sec^2$
TOPEX solar radiation pressure:	1.0%
TOPEX thermal radiation pressure:	$0.1 nm/sec^2$
Deep space network receiver station address:	5cm, each component
Pole shift:	1mas, each component
Zenith troposphere delay:	1cm deviation

6. Results

Since the major concern of our analysis is the radial component of the TOPEX orbit, the analysis results listed in this paper are limited to radial orbit errors alone. Owing to repeated Monte Carlo simulation, a realistic GPS orbit error was derived, and the error model was repeatedly adjusted until the final orbit error was similar to the real GPS orbit error. Then, with the error model derived, GPS-TOPEX simulation was conducted to look into the measurement component and dynamic component of the orbit error, respectively. The effects of these error sources on the TOPEX orbit determination based on the dynamic method are shown in Table 5. In addition, the GPS orbit was used to check the dynamic Consider Covariance analysis; OASIS was used

to conduct the sensitivity analysis of GPS-TOPEX orbit determination and the error value derived from MSODP determination were used to adjust the Consider Covariance analysis--all these led to the Consider Covariance error model as shown in Table 4.

Table 5 TOPEX Radial Orbit Error

Error Source	Specifications	Radial RMS(cm)
Measurement model error	Ambiguity parameters, zenith delay parameters adjustable	0.5
Gravitational model error	Ambiguous parameters adjustable	10.2
Non-gravitational model error	Ambiguous parameters adjustable Cd, Cr adjustable GPS, Cr, Y deviation adjustable	0.6
Total	Ambiguity, zenith delay parameters Cd and Cr of TOPEX GPS, Cr, Y deviation adjustable	9.7

7. Conclusions

Under the analysis and hypothesis conditions advanced in this paper, the orbit determination result of the simplified dynamic method proves to be superior to that from the kinematic and dynamic methods as long as the process noise does not appear too high ($\sigma<50nm/S^2$). Since the simplified dynamic method is virtually a combination of the short-arc segment solution principle, and the wise selection and restriction of "absorption" parameters, then the proper application of the"parameterized dynamics" short-arc solution method can possibly offer a similar result. In our analysis, however, the parameterized dynamics solution method was not taken into consideration and in this case, the optimal simplified dynamic method was found superior to the dynamic and kinematic methods in terms of orbit determination precision (including components at all locations).

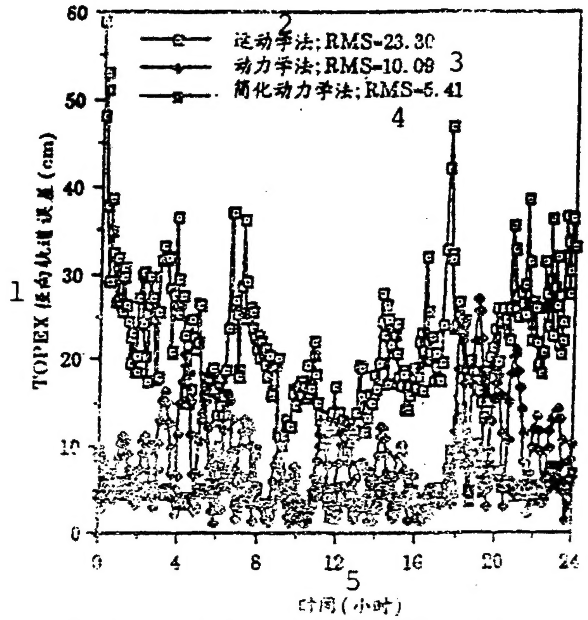

Fig. 2 TOPEX Radial Orbit Errors of Various Process Noise Values

Key: (1) TOPEX radial orbit error (cm); (2) Kinematic method; RMS=23.30; (3) Dynamic method; RMS=10.09; (4) Simplified dynamic method; RMS=5.41; (5) Time (hour)

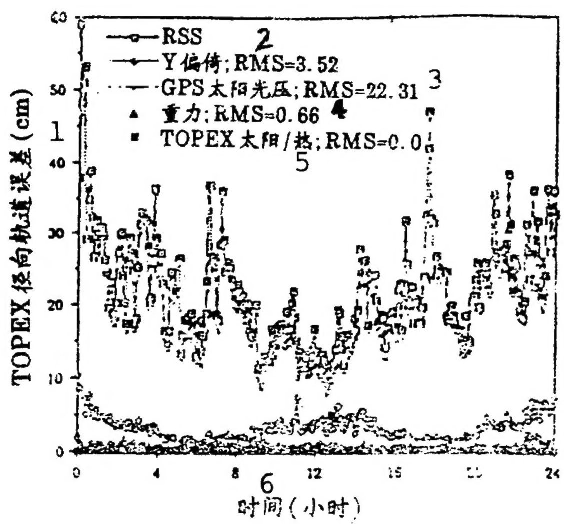

Fig. 3 TOPEX Radial Orbit Error Components in Kinematic Method

Key: (1) TOPEX radial orbit error (cm); (2) Y deviation; RMS=3.52; (3) GPS solar light pressure; RMS=22.31; (4) Gravity; RMS=0.66; (5) TOPEX sun/heat; RMS=0.0; (6) Time (hour)

图2 各种过程噪声值的TOPEX径向轨道误差

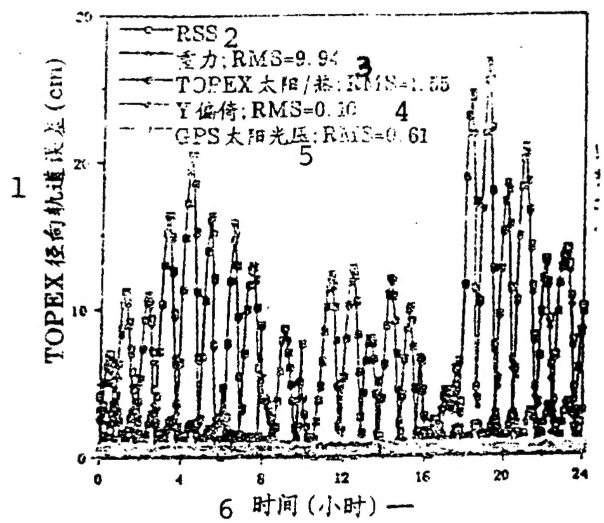

Fig. 4 TOPEX Radial Orbit Error Components in Dynamic Method
Key: (1) TOPEX radial orbit error (cm);
(2) Gravity; RMS=9.94; (3) TOPEX sun/heat; RMS=1.55;
(4) Y deviation; RMS=0.10; (5) GPS solar light pressure; RMS=0.61; (6) Time (hour)

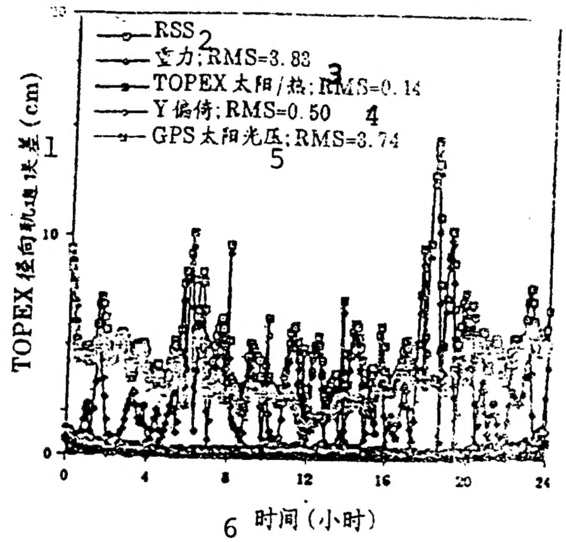

Fig. 5 TOPEX Radial Orbit Error Components in Simplified Dynamic Method

Key: (1) TOPEX radial orbit error (cm)
(2) Gravity; RMS=3.83
(3) TOPEX sun/heat; RMS=0.14
(4) Y deviation; RMS=0.50
(5) GPS solar light pressure; RMS=3.74
(6) Time (hour)

This paper was translated by Li Gefei and edited by Zhang Jisheng from "The Sixth International Geodetic Symposium On Satellite Positioning" (1992), P. 944-1003.

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